

DE LA RECHERCHE À L'INDUSTRIE



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The NEV FAR project:  
New Evaluation of  $\nu$  Fluxes At Reactors

# Revisiting the summation calculation of reactor antineutrino spectra

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IRN Neutrino meeting - 02/12/2021

# OUTLINE

## 1. Introduction & motivations

- a. Reactors as antineutrino sources
- b. Experimental anomalies

## 2. Different modeling methods

- a. Conversion method
- b. Reactor data-driven method
- c. Summation method

## 3. Revised summation method

- a.  $\beta^-$  spectrum calculation
- b. Nuclear data content
- c. Uncertainty budget

## 4. Preliminary comparisons

- a. Integral measurements
- b. Spectrum shape

## 5. Conclusion & perspectives

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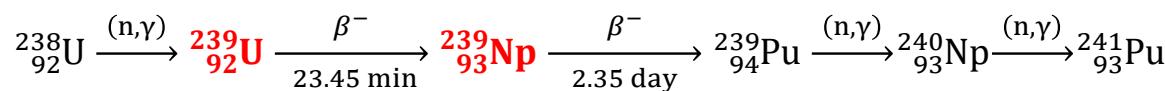
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# 1. Introduction & motivations

## a. Reactors as antineutrino sources

### PRESSURIZED WATER REACTOR (PWR)

- Fuel: lowly enriched uranium,  $^{238}\text{U} + 3\text{-}5\% \ ^{235}\text{U}$



- High power:  $\sim 3 - 4 \text{ GW}_{\text{th}}$
- Close reactor design & fuel contents for all PWR  
**⇒ close  $\bar{\nu}_e$  spectra**

	$\Phi [\bar{\nu}_e/\text{fis}]$	Contribution [%]	
<b>Fission</b>	$^{235}\text{U}$	3.3	46.3
	$^{239}\text{Pu}$	1.7	24.1
	$^{238}\text{U}$	0.5	7.3
	$^{241}\text{Pu}$	0.4	5.1
<b>Activation</b>	$^{239}\text{U}$	0.6	8.6
	$^{239}\text{Np}$	0.6	8.6
<b>Total</b>	<b>7.2</b>	100	

Average flux/fission for a Chooz type reactor ( $\sim 4\% \ ^{235}\text{U}$ ) over a 12-month core cycle

### RESEARCH REACTOR

- Fuel: highly enriched uranium,  $>20\% \ ^{235}\text{U}$
- Reactor specific structural material activation
  - e.g.  $^{27}\text{Al}$ ,  $^{55}\text{Mn}$ ,  $^9\text{Be}$ ,  $^{51}\text{V}$ , ...
- Low power :  $\sim 0.1 \text{ kW}_{\text{th}} - 100 \text{ MW}_{\text{th}}$  but very short baseline accessible
- Wide array of designs & fuel contents  
**⇒ reactor-specific  $\bar{\nu}_e$  spectra**

	$\Phi [\bar{\nu}_e/\text{fis}]$	Contribution [%]	
<b>Fission</b>	$^{235}\text{U}$	6.1	93.0
	$^{239}\text{Pu}$	<0.1	0.3
<b>Activation</b>	$^{239}\text{U}$	<0.1	0.2
	$^{239}\text{Np}$	<0.1	0.2
	$^{28}\text{Al}$	0.4	5.4
	$^{56}\text{Mn}$	0.1	0.9
<b>Total</b>	<b>6.5</b>	100	

Average flux/fission for the HFR at the ILL ( $\sim 93\% \ ^{235}\text{U}$ ) over a 50-day core cycle

**⇒  $\bar{\nu}_e$  contribution depends on reactor type and changes with time**

# 1. Introduction & motivations

## a. Reactors as antineutrino sources

Preliminary plots based on summation calculations

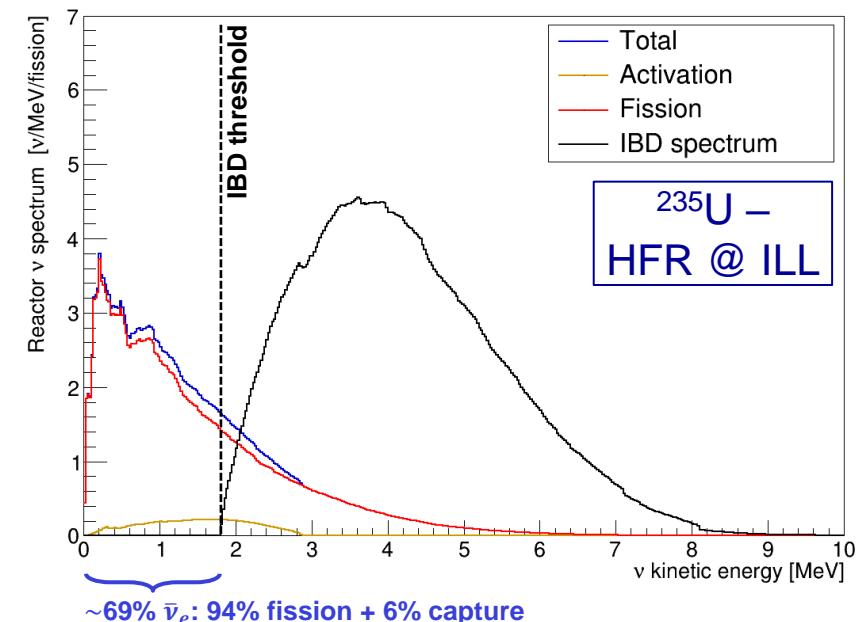
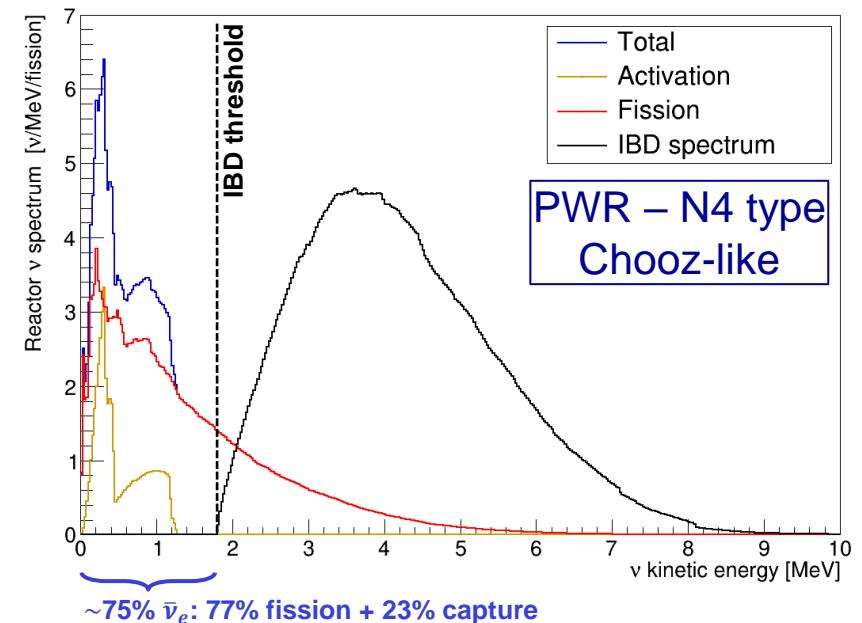
$$S_r(E, t) = \frac{P_{th}(t)}{\sum_f \alpha_f(t) \langle E_f \rangle} \left( \sum_a y_a(t) S_a(E) + \sum_f \alpha_f(t) S_f(E, t) \right)$$

Total
Fission rate
Activation
Fission

- $\langle E_f \rangle$ : mean energy released per fission  $\sim 200$  MeV
  - $P_{th}$ : reactor thermal power
  - $y_a$ : activation rate per fission
  - $\alpha_f$ : fission fraction
  - $S_a$ : activation  $\bar{\nu}_e$  spectrum
  - $S_f$ :  $\bar{\nu}_e$  fission spectrum
- } Provided by the plant  
 } Reactor simulation  
 } Spectrum predictions

$\Rightarrow$  Reactor  $\bar{\nu}_e$  flux  $\sim 2 \times 10^{20} \bar{\nu}_e \cdot s^{-1} \cdot GW_{th}$

$\Rightarrow$  Prediction needed for fission and activation spectra

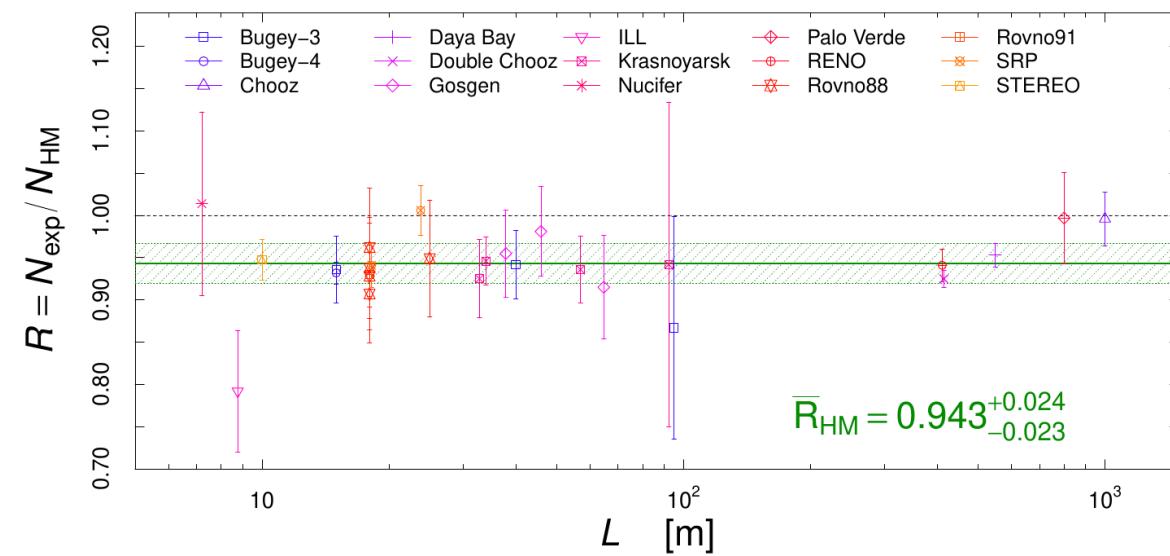


## REACTOR ANTINEUTRINO ANOMALY (RAA)

[Phys. Rev. D 83, 073006 \(2011\)](#)

- Systematic measured **IBD rate deficit** compared to HM
  - ▶ Observed in more than 20 reactor experiments
  - ▶ Confirmed in all recent reactor experiments at PWR and research reactors
- Ratio of measured over predicted IBD rate:  **$0.943 \pm 0.024$** 
  - ▶ Statistical significance:  **$2.4\sigma$**
- RAA possible origins
  - ▶ Experimental bias
  - ▶ New physics (sterile neutrino)
  - ▶ **Mismodeling / underestimation of  $\bar{\nu}_e$  spectrum uncertainty**

[J. High Energ. Phys. 2017, 135 \(2017\)](#)  
[Updated plot from TAUP 2021](#)



# 1. Introduction & motivations

## b. Experimental anomalies

### REACTOR ANTINEUTRINO ANOMALY (RAA)

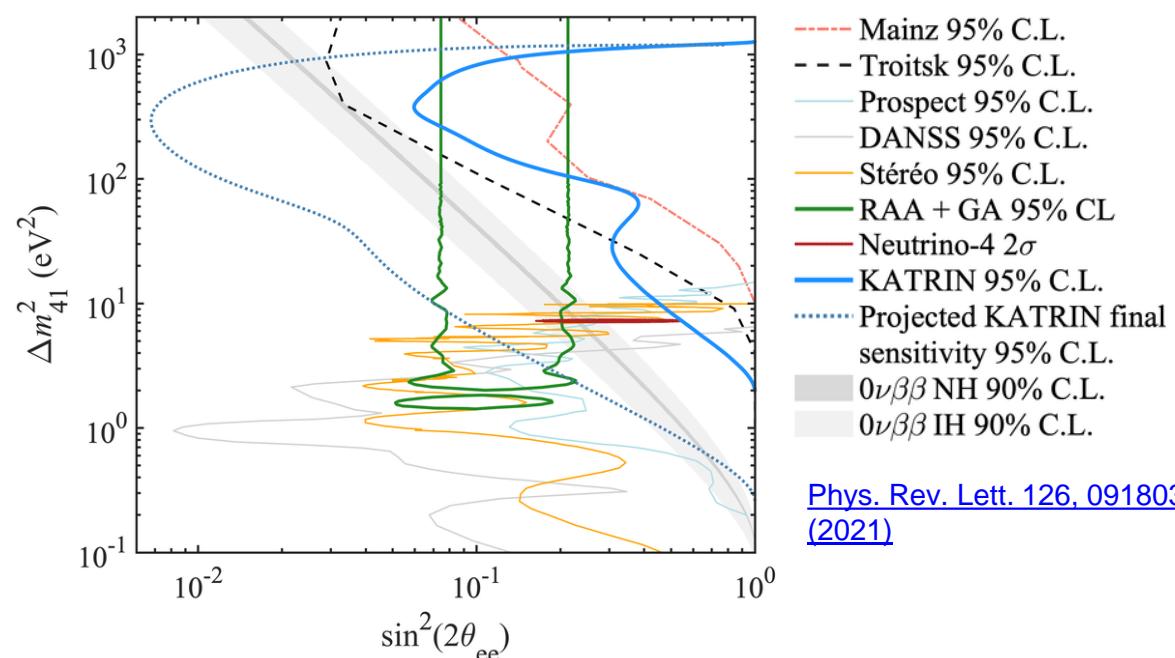
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} Unlikely

Experiment	Power [MW <sub>th</sub> ]	Baseline [m]	Overburden [m.w.e]	Target material	Segment
DANSS	3100	10.7-12.7	50	Gd layer PS	2D
NEOS	2800	24	20	Gd LS	None
STEREO	55	10	15	Gd LS	1D
PROSPECT	80	7-13	Surface	<sup>6</sup> Li LS	2D
Neutrino-4	100	6-12	Surface	Gd LS	2D
SoLid	50-80	5.5-12	10	<sup>6</sup> Li layer LS	3D

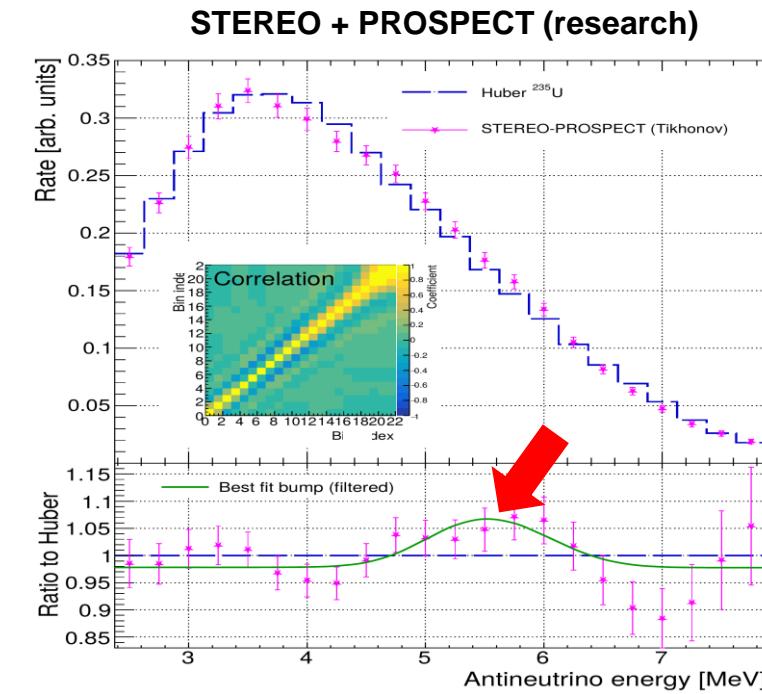
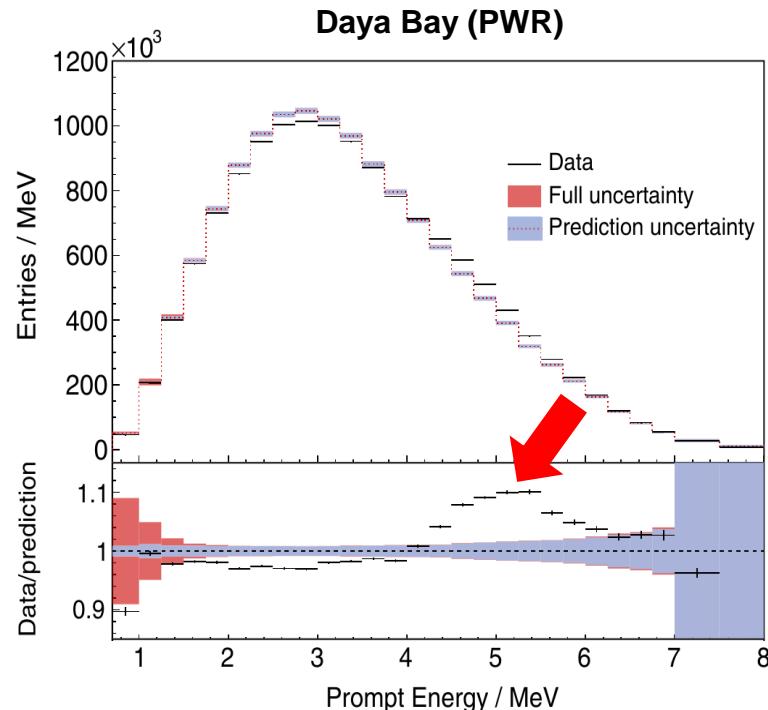
Overview of the on-going experimental efforts to detect active-sterile oscillation at nuclear reactors



## SHAPE ANOMALY

- First observed by Double Chooz, Daya Bay and RENO
  - ▷ Confirmed by recent very-short baseline reactor experiments (NEOS, STEREO, PROSPECT, DANSS)

- Possible origins
  - ▷ ~~Detector energy scale calibration~~
  - ▷ ~~Fuel composition~~
  - ▷ **Prediction issue, single / multiple actinide(s) ?**



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## 2. Different modeling methods

### a. Conversion method

#### CONVERSION METHOD

- Measure **experimental  $\beta$  fission spectra** from neutron-irradiated targets
  - ▷  $^{235}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$  from Schreckenbach *et al.*, HFR reactor at ILL (1980's)
  - ▷  $^{235}\text{U}/^{239}\text{Pu}$  from Kopeikin *et al.*, IR-8 reactor at KI (2021)
  - ▷  $^{238}\text{U}$  from Haags *et al.*, FRM-II reactor at Garching (2013)
- Fit  $\beta$  fission spectrum with virtual  $\beta$  branches and convert to  $\bar{\nu}_e$  branches
- Independent revisions in 2011 by Saclay and P. Huber
  - ▷ Used in state-of-the-art predictions → **Huber-Mueller prediction (HM)**



#### PROS

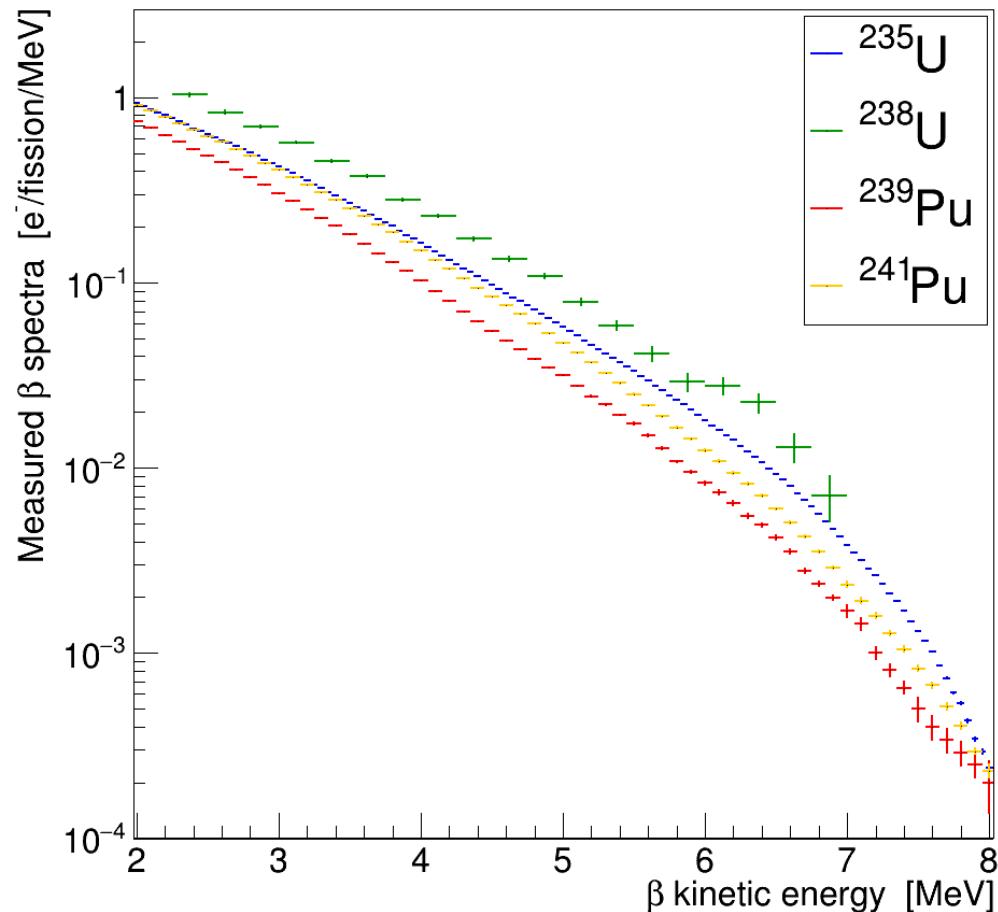
- Small experimental uncertainties  $\sim 2\text{-}3\%$
- Access to total  $\bar{\nu}_e$  fission spectrum



#### CONS

- Limited to experimental range, 2-8 MeV
- No activation spectrum
- **HM subject to the anomalies**

#### ILL spectra & $^{238}\text{U}$ Garching spectrum



## 2. Different modeling methods

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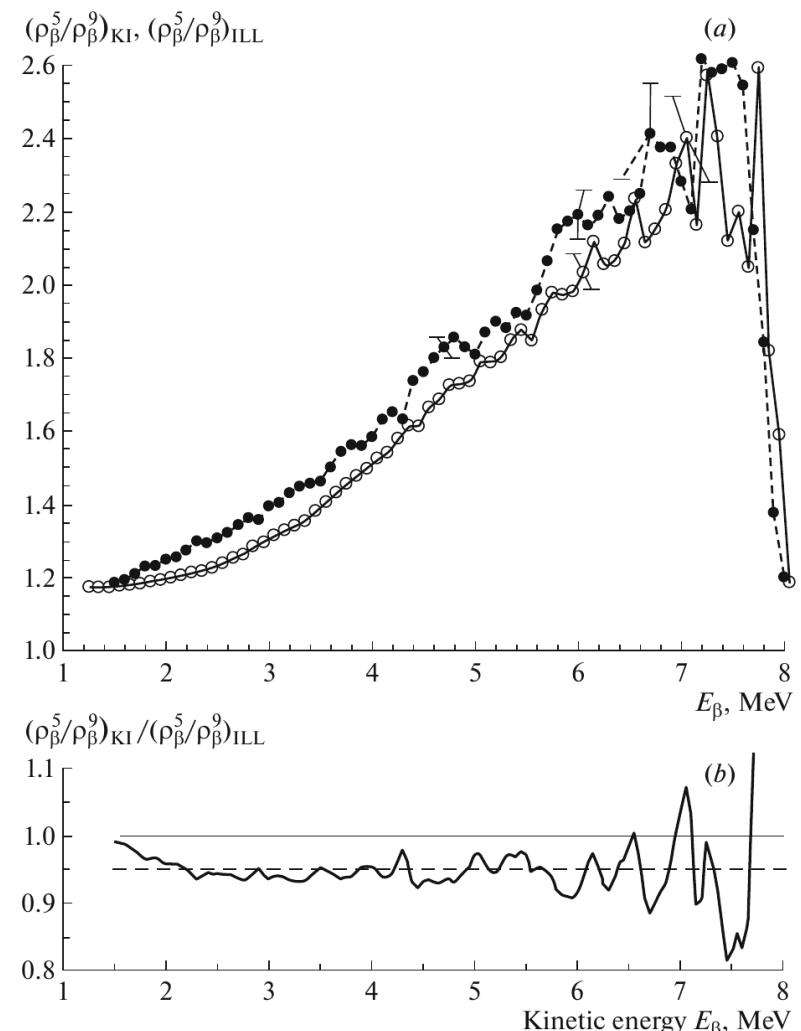
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- Limited to experimental range, 2-8 MeV
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- Disagreement between  $\beta$  fission spectra datasets

Kopeikin, Phy. At. Nuc. 84 (2021)



⇒ Ratios  $^{235}\text{U}/^{239}\text{Pu}$  ( $\beta$  spectrum) at Kurchatov Institute (KI) lower by  $\sim 5\%$  than ILL's measurement

## 2. Different modeling methods

### a. Conversion method

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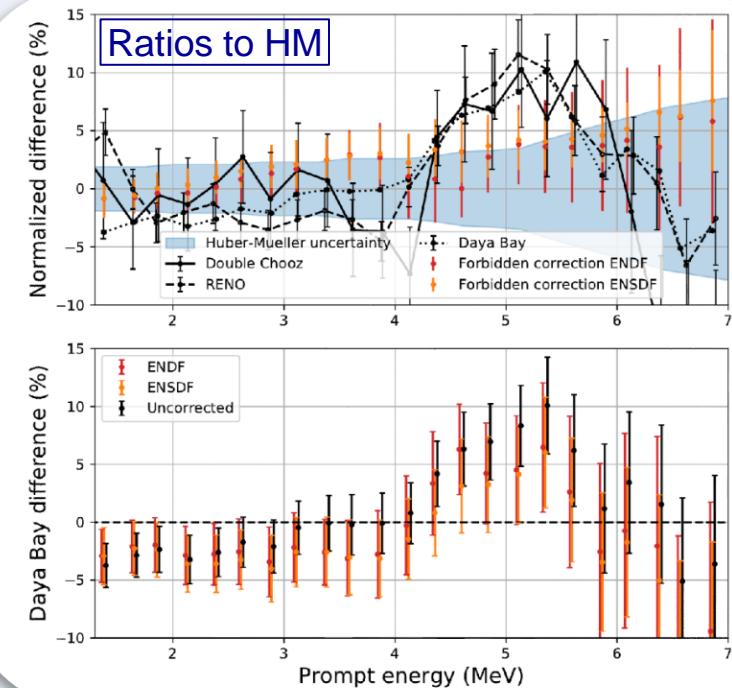


#### CONS

- Limited to experimental range, 2-8 MeV
- No activation spectrum
- **HM subject to the anomalies**
- Disagreement between  $\beta$  fission spectra datasets
- Modeling of virtual branches with allowed branches

#### THE ROLE OF FORBIDDEN TRANSITIONS

- Hayen *et al.* (2019): nuclear structure calculation for non-unique transition shape factors (HKSS model)
  - Hayes *et al.* (2014): weak magnetism corrections for forbidden transitions
- ⇒ **Increased uncertainty + partial explanation of the shape anomaly**



Phys. Rev. C 100, 054323 (2019)

## 2. Different modeling methods

### b. Reactor data-driven method

#### REACTOR DATA-DRIVEN METHOD

- Unfolding an **experimental**, prompt IBD spectrum  $\rightarrow \bar{\nu}_e$  spectrum + covariance matrix
  - ▷ **Daya Bay**: Total,  $^{235}\text{U}$ ,  $^{239}\text{Pu} + ^{241}\text{Pu}$  (Pu combo)
  - ▷ **RENO, NEOS**: Total
  - ▷ **STEREO, PROSPECT**:  $^{235}\text{U}$
- Detailed procedure in [Chinese Phys. C 45 073001 \(2021\)](#)



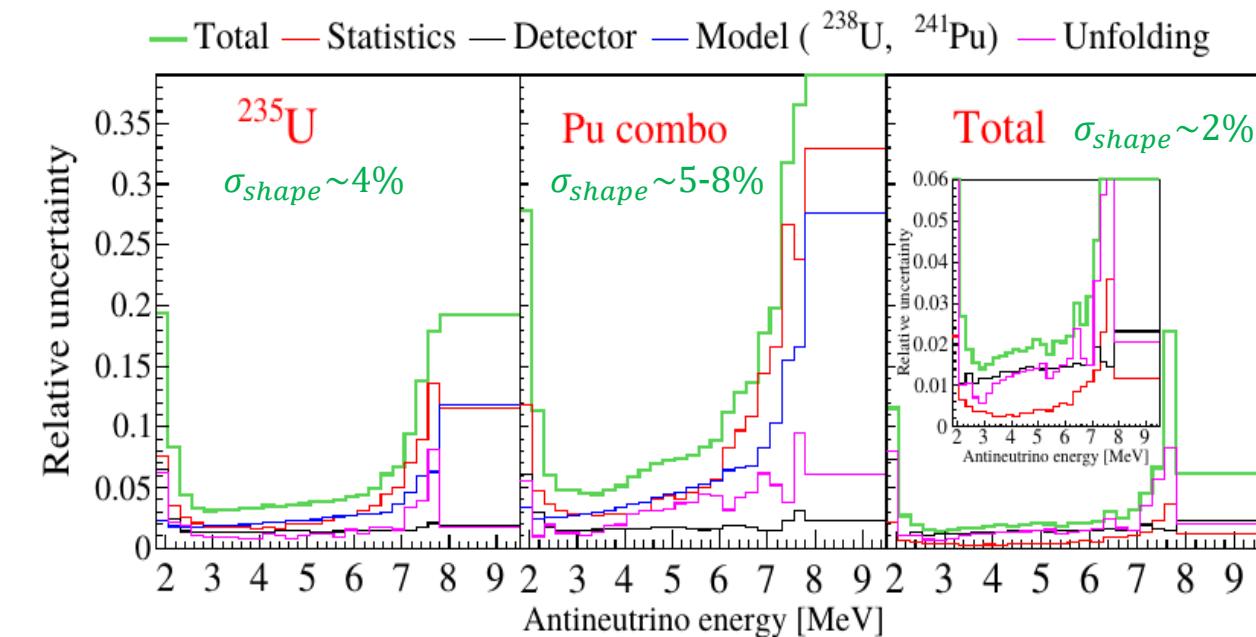
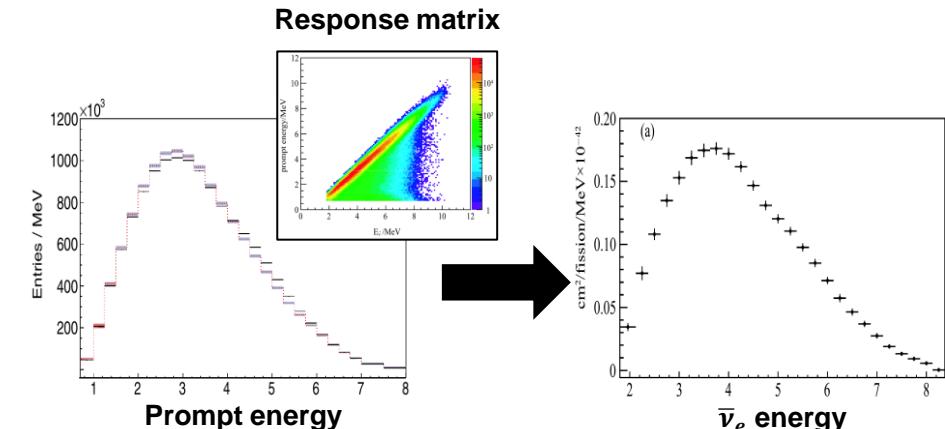
#### PROS

- Model-independent, not subject to anomalies
- Small uncertainties



#### CONS

- Limited to experimental range, 1.8-9 MeV
- Small number of available datasets
- No activation spectrum



[Chinese Phys. C 45 073001 \(2021\)](#)

## SUMMATION METHOD

- Fission spectrum prediction = sum of all  $\beta^-$  branches listed in nuclear databases
  - ▷ +900  $\beta^-$  emitters ~ 10 000  $\beta^-$  transitions
- $^{238}\text{U}$  from Mueller *et al.* (2011)
  - ▷ Several approximations + rough uncertainty model



### PROS

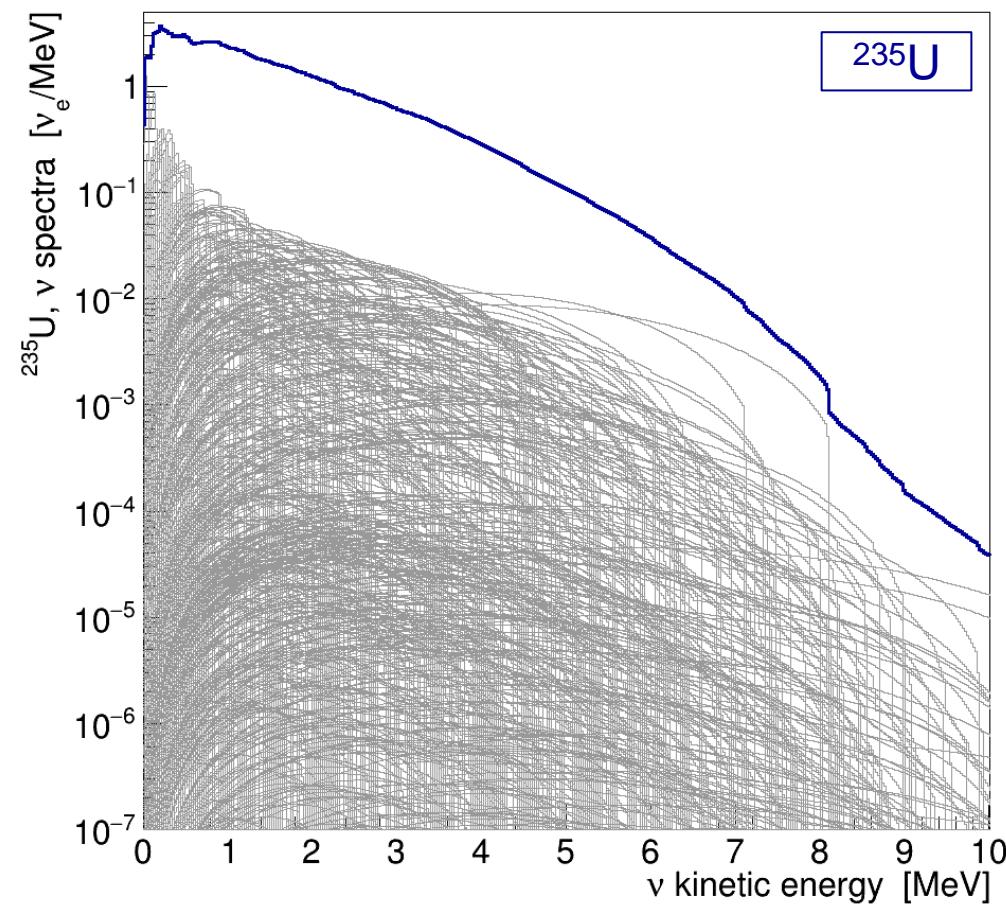
- Prediction  $\forall$  energy,  $\forall \beta^-$  emitter
- Convenient to understand physics
- Mandatory for activation spectra



### CONS

- Uncomplete/biased nuclear database
- Modeling approximations
- Systematic uncertainties very complicated to estimate

⇒ Reliable summation method required for multiple purposes



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## THE PANDEMONIUM EFFECT

- Estienne-Falot model (EF): include Pandemonium-free data from Total absorption  $\gamma$  spectroscopy (TAGS)

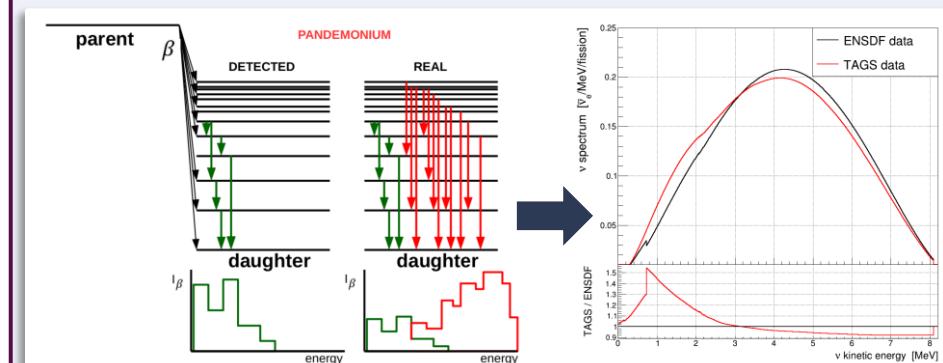


Illustration of the Pandemonium effect impact on the  $\bar{\nu}_e$  spectrum of  $^{92}\text{Rb}$ .

## 2. Different modeling methods

### c. Summation method

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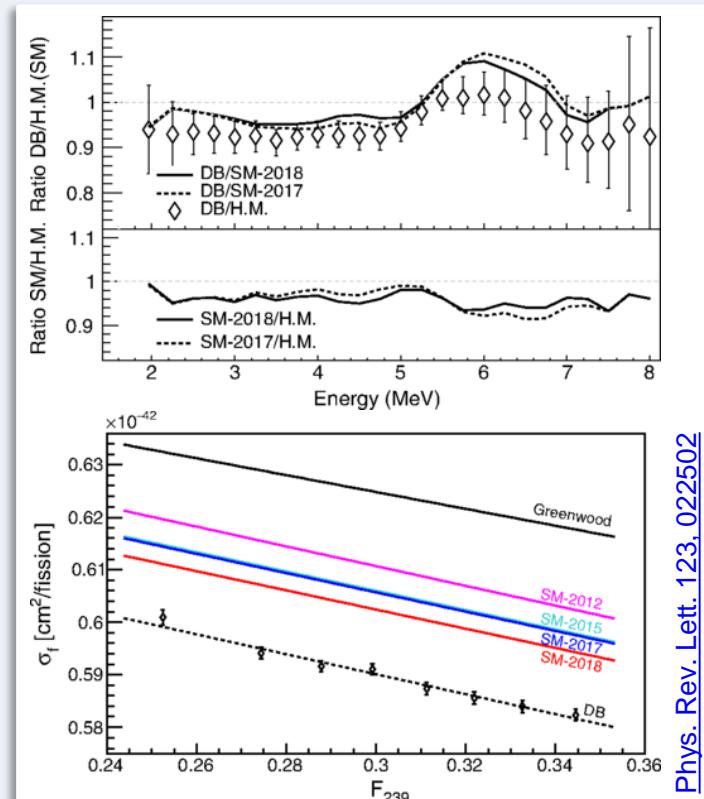
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#### THE PANDEMONIUM EFFECT

- Estienne-Falot model (EF): include Pandemonium-free data from Total absorption  $\gamma$  spectroscopy (TAGS)

⇒ **Decrease IBD yield and shape differences**

⇒ **Very important IBD contribution but no uncertainty budget**



Phys. Rev. Lett. 123, 022502

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## THE NEvFAR PROJECT

(New Evaluation of  $\nu$  Fluxes At Reactor)



- Revise summation method with BESTIOLE code
  - ▷ Improve  $\beta^-$ -decay modeling
    - Refine forbidden transition modeling
  - ▷ Impact of database uncompleteness and quality
    - Update nuclear database with Pandemonium-free data
    - Adjusted effective modeling for isotopes with no data
  - ▷ Build a comprehensive uncertainty budget
    - Nuclear data and modeling uncertainties



**On-going work: all results are preliminary**

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#### a. $\beta^-$ spectrum calculation

W. Bühring and H. Behrens formalism (1986)

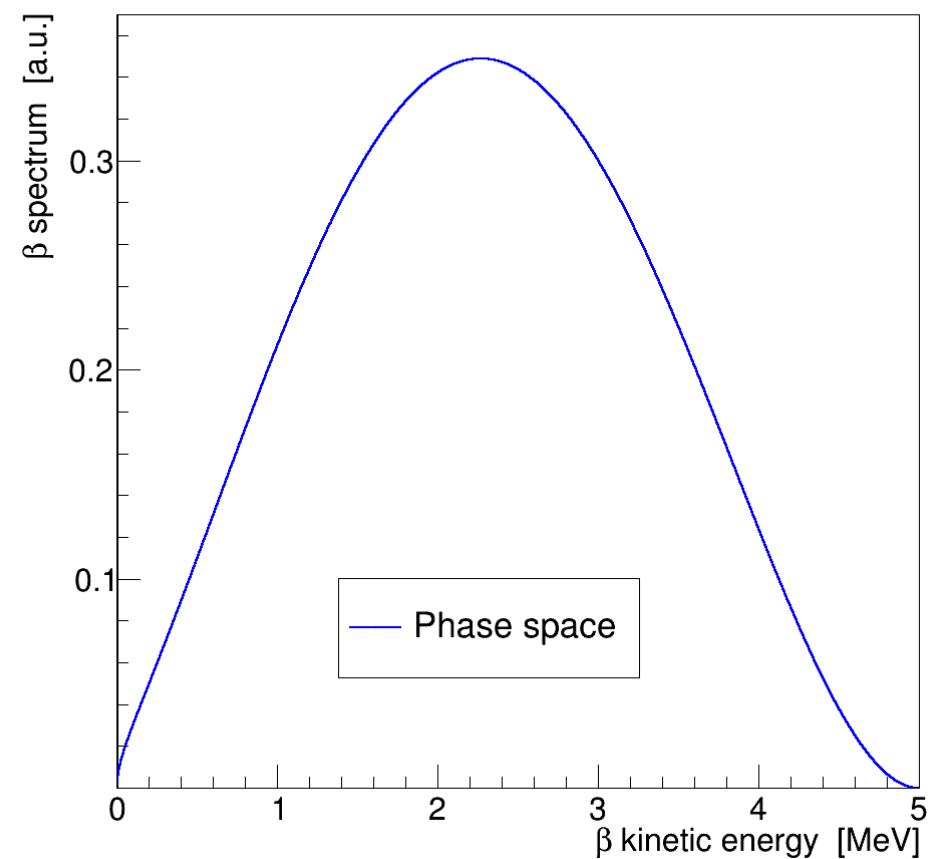
#### V-A THEORY OF $\beta$ -DECAY

- $p$ :  $\beta$  momenum
- $W$ :  $\beta$  total energy
- $W_0$ : max available energy
- $E_0 = W_0 - m_e$ : max kinetic energy

$$S_\beta(Z, A, W) = K [pW(W_0 - W)^2 F_0(Z, A, W) C(Z, A, W) (1 + \delta_{WM} + \delta_{RC})]$$

- Phase space

▷ Energy states accessible to the emitted  $\beta$



### 3. Revised summation method

#### a. $\beta^-$ spectrum calculation

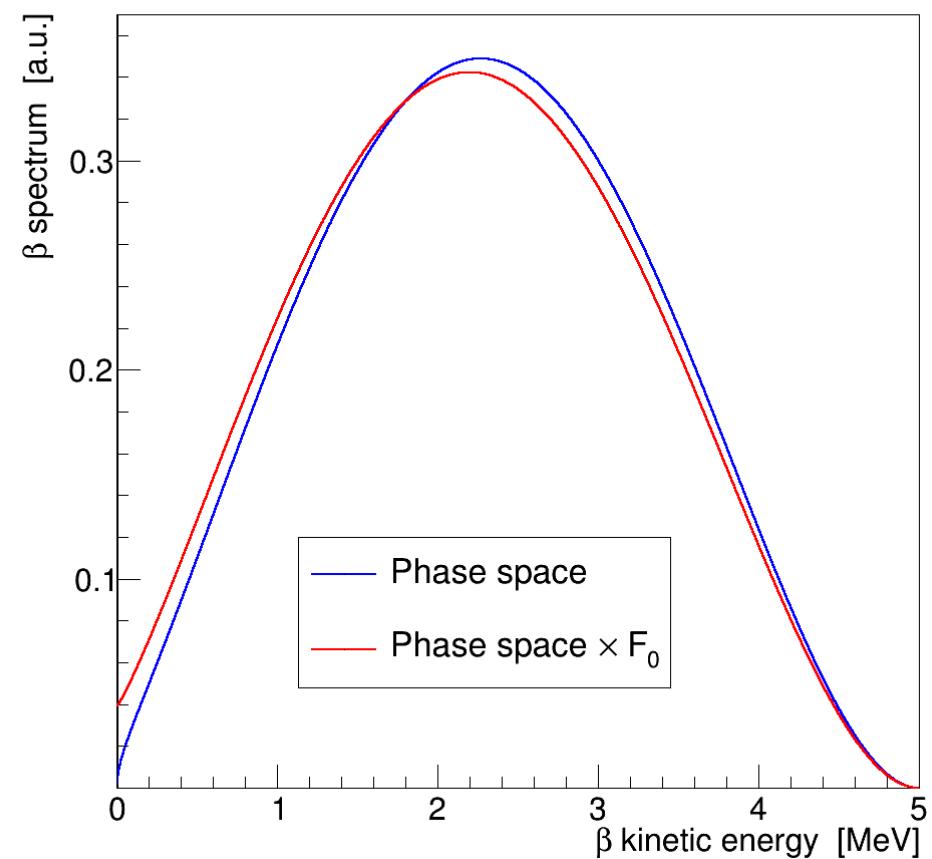
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- Phase space
  - ▷ Energy states accessible to the emitted  $\beta$
- Fermi function
  - ▷ Electromagnetic interaction  $\beta$  / daughter nucleus
  - ▷ Depends on  $\beta$  wavefunction



### 3. Revised summation method

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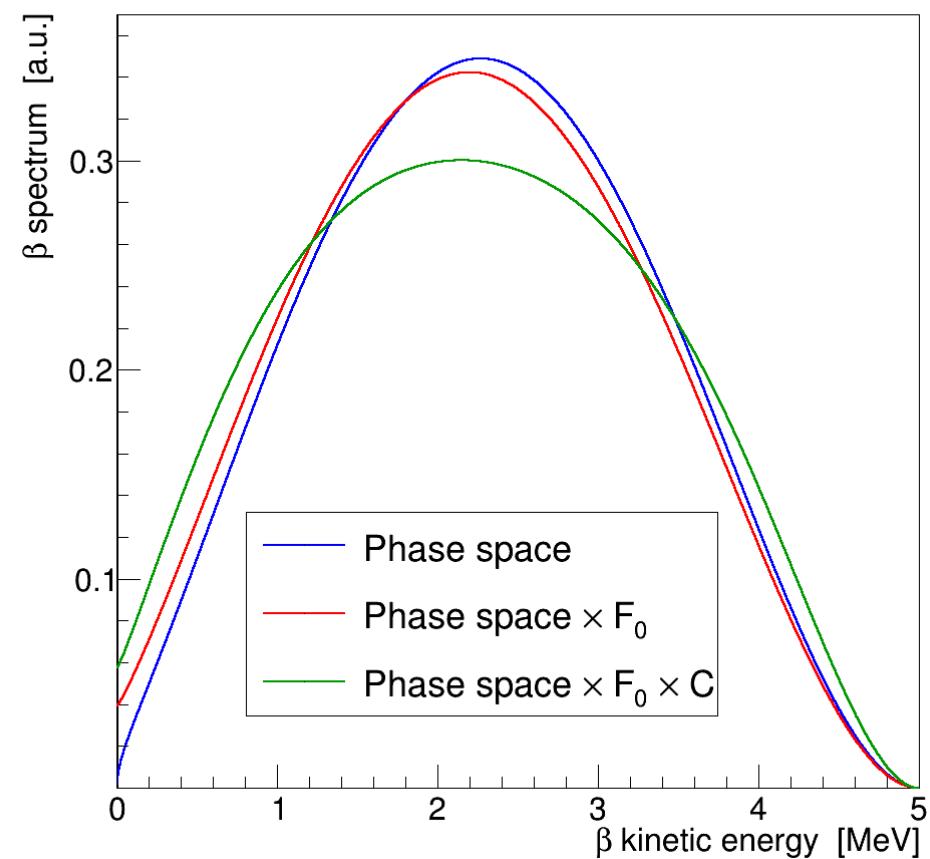
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  - ▷ Depends on  $\beta$  wavefunction
- Shape factor
  - ▷ Nuclear structure effect, depends on spin-parity
  - ▷ Depends on  $\beta$  wavefunction



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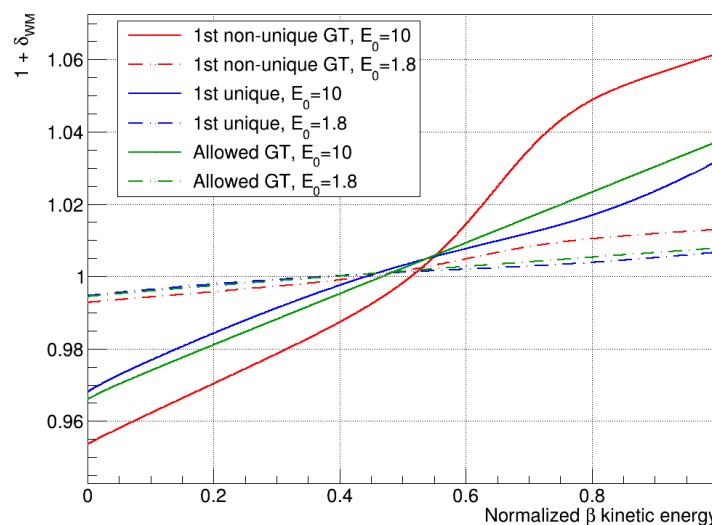
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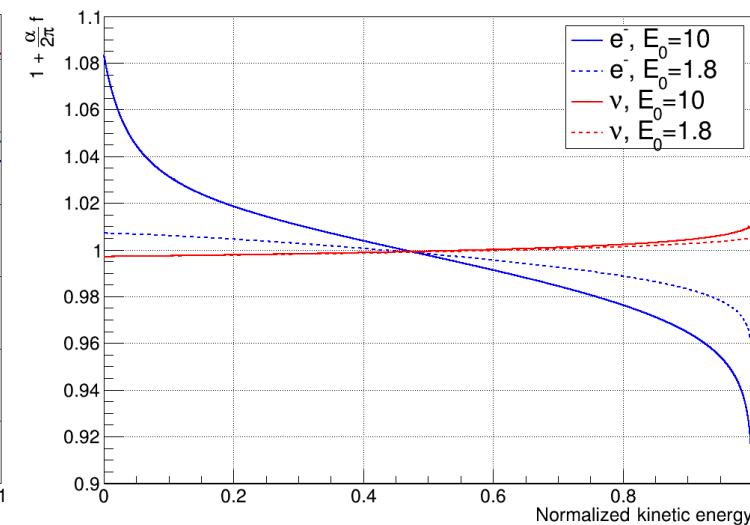
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- Weak magnetism correction (WM)
  - ▷ Nucleon structure effect
  - ▷ Depends on spin-parity info
- Radiative correction (RC)
  - ▷ QED effect from virtual photon exchange
  - ▷  $\beta$  correction  $\gg \bar{v}_e$  correction
- Normalization factor:  $\int dW S_\beta = 1$

#### V-A THEORY OF $\beta$ -DECAY



[Hayes et al., Phys. Rev. Lett. 112, 202501 \(2014\)](#)



Correction  $\beta$ : [Sirlin, Phys. Rev. 164, 1767 \(1967\)](#)

Correction  $\bar{v}_e$ : [Sirlin, Phys. Rev. D 84, 014021 \(2011\)](#)

CLASSIFICATION OF  $\beta^-$  TRANSITIONS

$\beta$ -decay type	$\Delta J$	$\pi_i \pi_j$	Shape factor	Calculation	$\bar{\nu}_e$ [%]	IBD [%]
Allowed	0,1	+1	1	<i>Robust and accurate</i>	62	53
Unique forbidden	$n + 1$	$(-1)^n$	Polynomial in $p_v$ & $p_e$		10	9

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1 <sup>st</sup> non-unique forbidden	0,1	-1			25	37
Main ( $\varphi_{IBD} \geq 1\%$ )			Nuclear struct. calcul.	<i>Advanced calculation</i>	5	21
Others					20	16
$n^{\text{th}}$ non-unique forbidden	$n$	$(-1)^n$	$\xi$ -approximation	<i>Unknown accuracy</i>	3	1

## NON-UNIQUE FORBIDDEN SHAPE FACTOR

- No simple expression
  - ▷ Depends on **transition matrix elements** connecting nuclear states
  - ▷ Nuclear structure calculations or  $\xi$ -approximation

CLASSIFICATION OF  $\beta^-$  TRANSITIONS

$\beta$ -decay type	$\Delta J$	$\pi_i \pi_j$	Shape factor	Calculation	$\bar{\nu}_e$ [%]	IBD [%]
Allowed	0,1	+1	1		62	53
Unique forbidden	$n + 1$	$(-1)^n$	Polynomial in $p_v$ & $p_e$	<i>Robust and accurate</i>	10	9
1 <sup>st</sup> non-unique forbidden	0,1	-1			25	37
Main ( $\varphi_{IBD} \geq 1\%$ )			Nuclear struct. calcul.	<i>Advanced calculation</i>	5	21
Others					20	16
$n^{\text{th}}$ non-unique forbidden	$n$	$(-1)^n$	$\xi$ -approximation	<i>Unknown accuracy</i>	3	1

## NON-UNIQUE FORBIDDEN SHAPE FACTOR

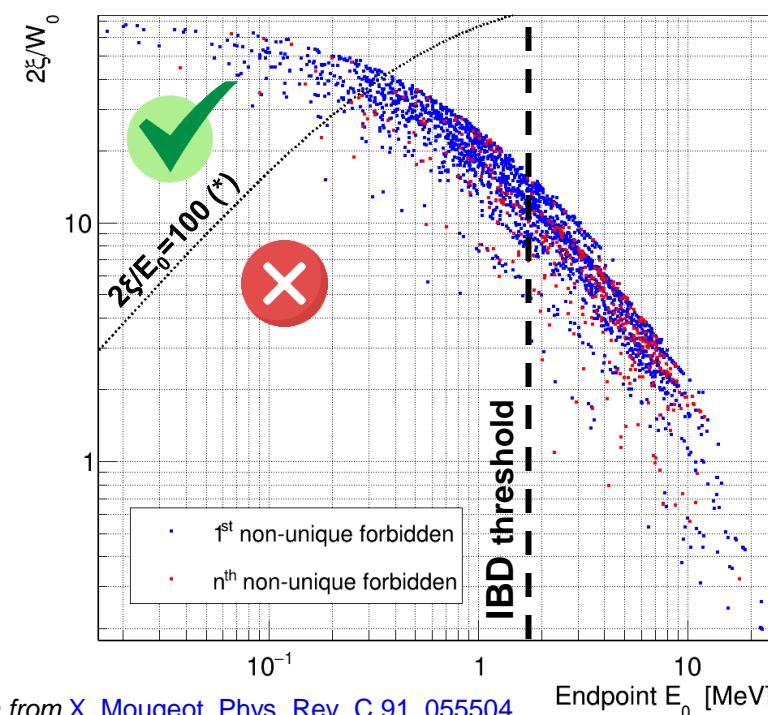
- No simple expression
  - Depends on **transition matrix elements** connecting nuclear states
  - Nuclear structure calculations or  $\xi$ -approximation

 $\xi$ -approximation

$$2\xi = \alpha Z / R_n \gg W_0$$

- $\alpha$ : fine structure constant
- $R_n$ : radius of the daughter
- $W_0$ : max available energy for the transition

- If verified:  $n^{\text{th}}$  non-unique  $\sim (n - 1)^{\text{th}}$  unique
- Applied to all non-unique transitions → **induce mismodeling**
  - Except 11 important non-unique transitions**



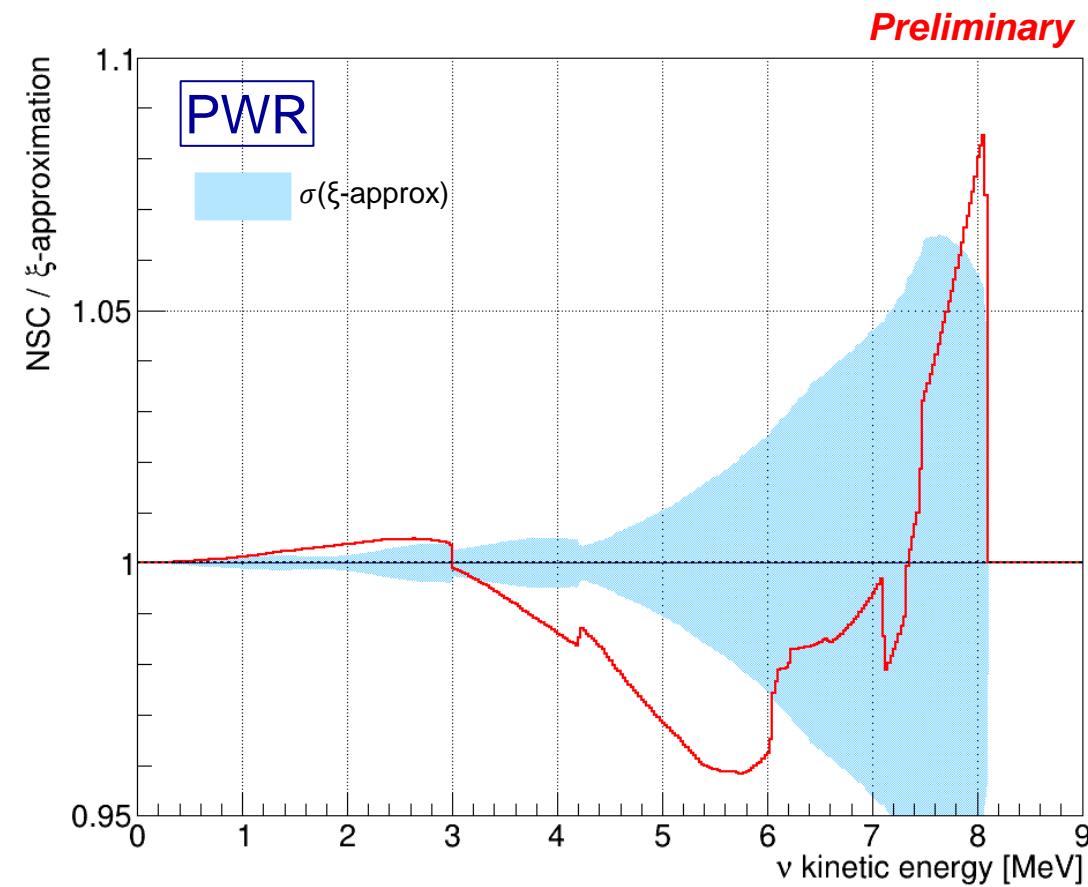
(\*): Criterion from X. Mougeot, Phys. Rev. C 91, 055504

## NUCLEAR STRUCTURE CALCULATION (NSC)

- $\beta$ -decay = single nucleon transition
- Nuclear state = superposition of nucleon states
- Non-unique shape factor calculation with NuShellX program
  - ▷ Very time (man & cpu) consuming
  - ▷ Comprehensive calculation for 11 important non-unique transitions

**Main 1<sup>st</sup> non-unique transition contributions  
with NSC calculation for a Chooz-like PWR**

Isotope	$^{92}\text{Rb}$	$^{96}\text{Y}$	$^{142}\text{Cs}$	$^{140}\text{Cs}$	$^{137}\text{I}$	$^{135}\text{Te}$	$^{139}\text{Cs}$	$^{95}\text{Sr}$	$^{90}\text{Rb}$	$^{93}\text{Rb}$
$E_0$ [MeV]	8.1	7.1	7.3	6.2	7.5	6.1	4.2	6.1	7.5	6.1
IBD [%]	5.1	4.9	1.7	1.6	1.3	1.3	1.2	1.2	1.0	1.0
Cumul.	5.1	10.0	11.8	13.3	14.6	15.9	17.1	18.3	19.3	20.3



⇒ IBD yield decreased by 1.5%  
compared to full  $\xi$ -approximation

⇒ Importance of correct treatment of non-unique transitions + derived uncertainty

### 3. Revised summation method

### b. Nuclear data content

#### Angeli 2013

- Nuclear radius ( $R_n$ )  
[Angeli et al., At. Data Nucl. Data Tables 99\(1\):69-95 \(2013\)](#)

#### ENSDF-2020

- Branching ratio (BR)
- $\beta^-$  intensity ( $I_\beta$ )
- Spin-parity ( $J\pi$ )
- Parent energy ( $E_{parent}$ )
- Daughter level energy ( $E_{lvl}$ )

#### NUBASE-2020

- $\beta^-$  intensity ( $I_\beta$ )
- Parent energy ( $E_{parent}$ )

#### AME-2020

- $Q_\beta$  energy

#### JEFF-3.3

- Fission yield (FY)

#### Branch spectrum

$$S_\beta = K p W (W_0 - W)^2 F_0 C (1 + \delta_{WM} + \delta_{RC})$$

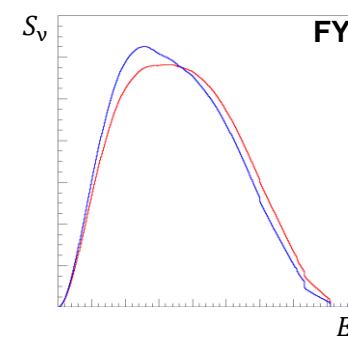
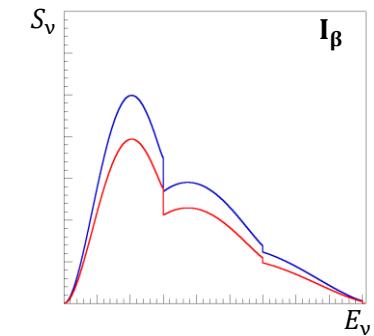
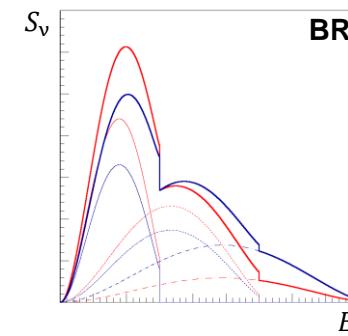
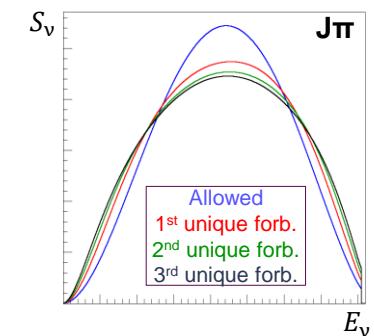
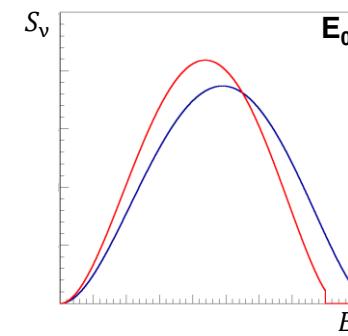
#### Isotope spectrum

$$S_i = \sum_b BR_i^b S_v^b$$

#### Fission spectrum

$$S_f = \sum_i FY_f^i S_i$$

$$E_0 = Q_\beta + E_{parent} - E_{lvl}$$



⇒ Summation method requires many input data

### 3. Revised summation method

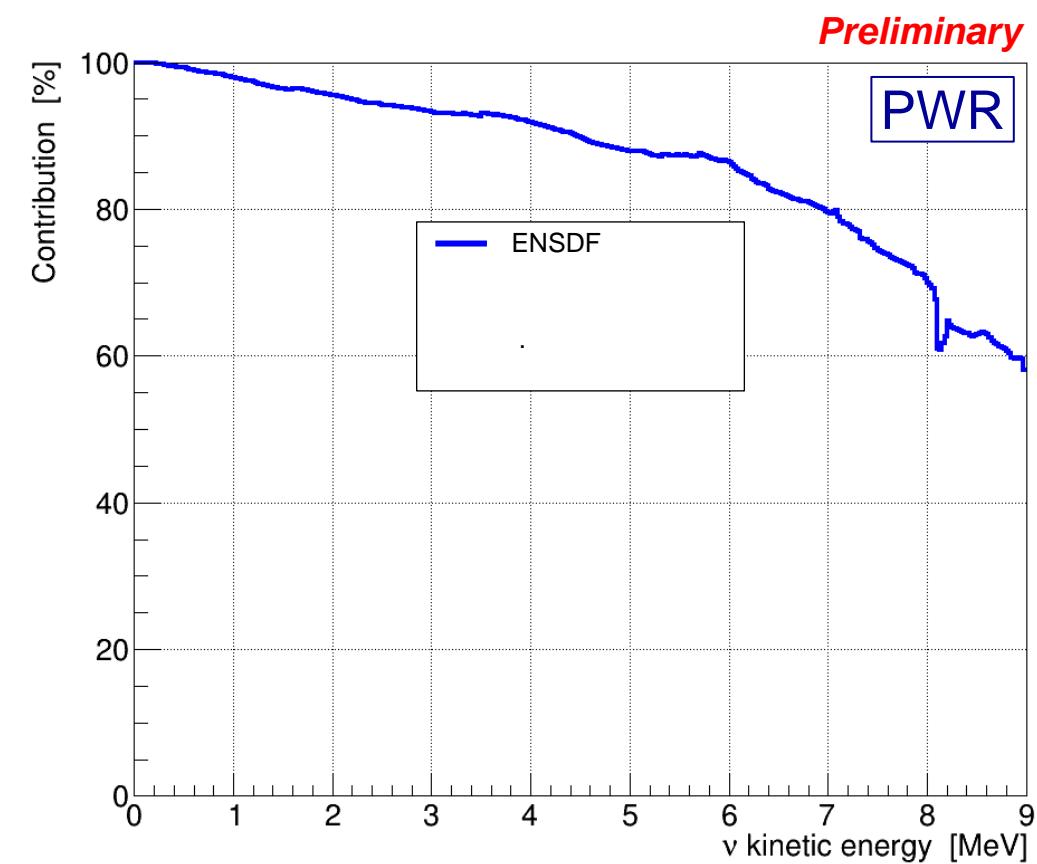
### b. Nuclear data content

$\beta^-$ emitters from JEFF-3.3		
	NUBASE-2020	ENSDF-2020
$^{235}\text{U}$	793	574
$^{238}\text{U}$	778	544
$^{239}\text{Pu}$	851	633
$^{241}\text{Pu}$	860	611
PWR $\bar{\nu}_e$ flux contribution [%]		97
PWR IBD yield contribution [%]		90

**2 issues with ENSDF database**

- Database completeness
- Quality of experimental data and evaluation

⇒ Pandemonium effect

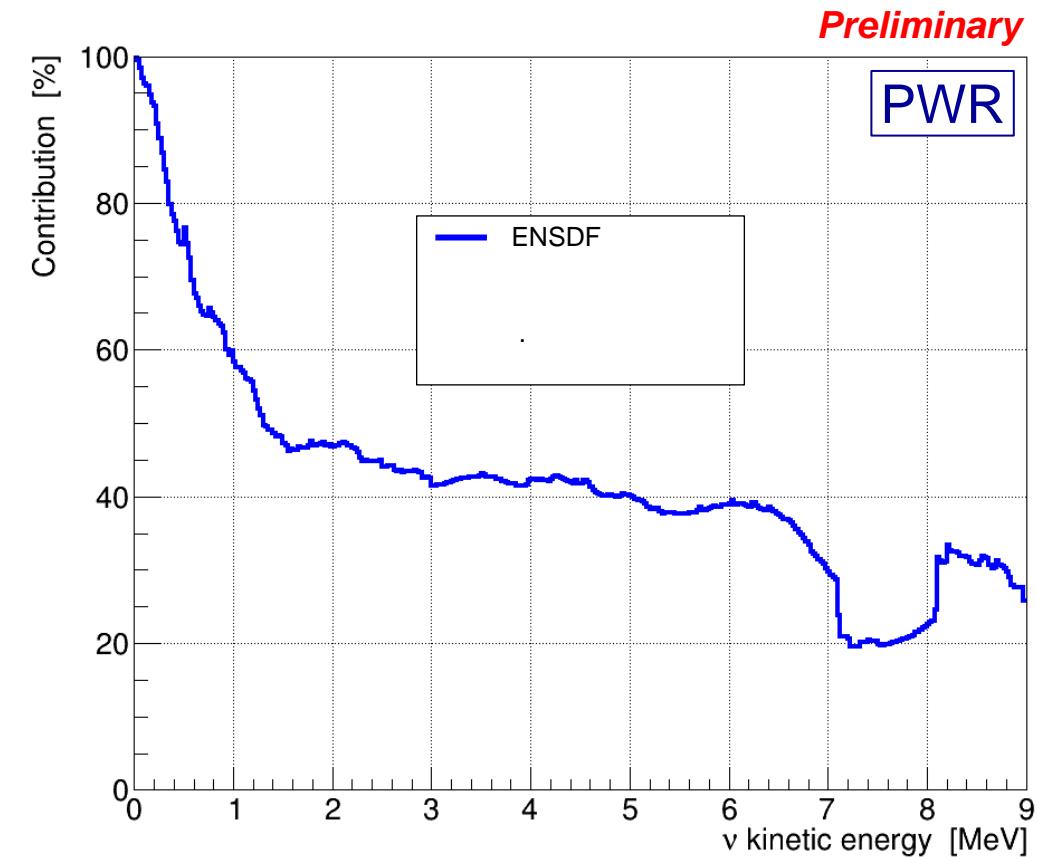


### 3. Revised summation method

### b. Nuclear data content

$\beta^-$ emitters from JEFF-3.3		
	NUBASE-2020	ENSDF-2020
$^{235}\text{U}$	793	↓ 460
$^{238}\text{U}$	778	↓ 430
$^{239}\text{Pu}$	851	↓ 519
$^{241}\text{Pu}$	860	↓ 497
PWR	$\bar{\nu}_e$ flux contribution [%]	↓ 60
PWR	IBD yield contribution [%]	↓ 41

2 issues with ENSDF database  
• Database completeness  
• Quality of experimental data and evaluation  
⇒ Pandemonium effect



### 3. Revised summation method

### b. Nuclear data content

$\beta^-$ emitters from JEFF-3.3				
	NUBASE-2020	ENSDF-2020	TAGS*	Direct $\beta^{**}$
$^{235}\text{U}$	793	460	71 (42)	43
$^{238}\text{U}$	778	430	71 (42)	43
$^{239}\text{Pu}$	851	519	71 (42)	43
$^{241}\text{Pu}$	860	497	71 (42)	43
PWR	$\bar{\nu}_e$ flux contribution [%]	<b>60</b>	<b>30 (19)</b>	<b>8</b>
PWR	IBD yield contribution [%]	<b>41</b>	<b>40 (16)</b>	<b>10</b>

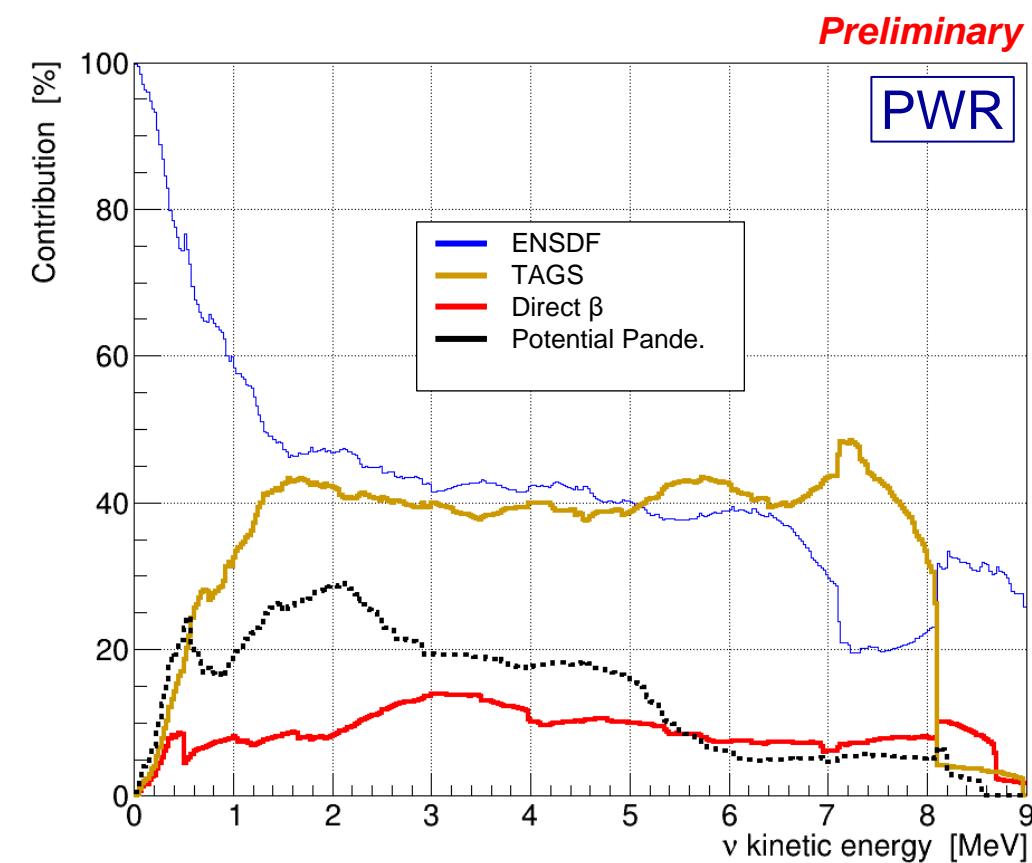
\*Potential Pande. in parenthesis, list from [INDC\(NDS\) - 0551. IAEA \(2009\)](#) and [INDC\(NDS\) – 0676. IAEA \(2015\)](#)

\*\*[Rudstam et al., At. Data Nucl. Data Tables 45\(2\):239-320 \(1990\)](#)

- Pandemonium-free data**
- Priority over ENSDF data
  - TAGS priority over Direct  $\beta$

⇒ IBD yield decreased by 13% with Pandemonium-free data

⇒ Expected to further decrease by ~2% with future measurements  
 → derived uncertainty



#### Quality of nuclear data

- Acceptable: ENSDF, TAGS, Direct  $\beta$
- Questionable: potential Pandemonium
  - 42 isotopes identified
  - Measurement needed

### 3. Revised summation method

### b. Nuclear data content

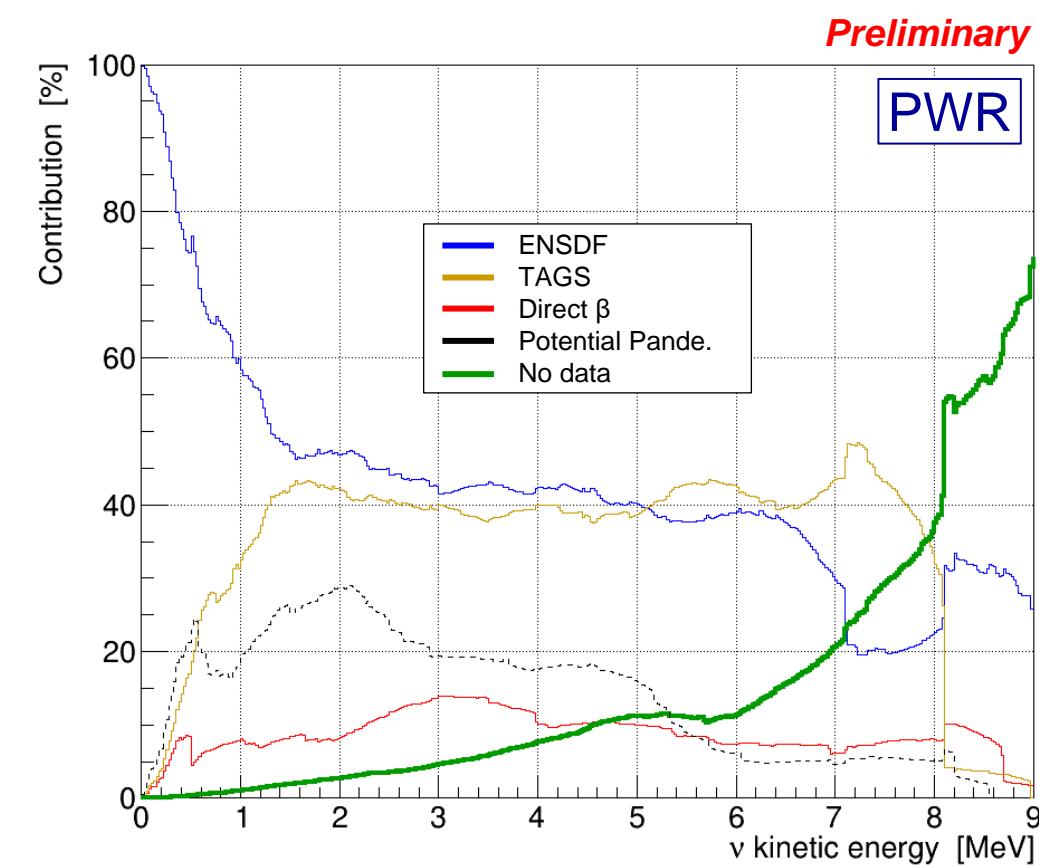
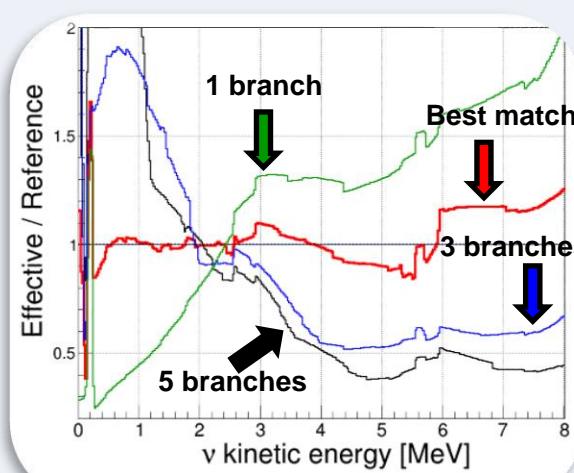
$\beta^-$ emitters from JEFF-3.3					
	NUBASE-2020	ENSDF-2020	TAGS	Direct $\beta$	No data
$^{235}\text{U}$	793	460	71 (42)	43	219
$^{238}\text{U}$	778	430	71 (42)	43	234
$^{239}\text{Pu}$	851	519	71 (42)	43	218
$^{241}\text{Pu}$	860	497	71 (42)	43	249
PWR $\bar{\nu}_e$ flux contribution [%]	<b>60</b>	<b>30 (19)</b>	<b>8</b>		<b>2</b>
PWR IBD yield contribution [%]	<b>41</b>	<b>40 (16)</b>	<b>10</b>		<b>9</b>

### NEW $Q_\beta$ EFFECTIVE MODELING

- Same virtual decay scheme applied (in relative) to all isotopes with no data
  - Virtual transition = allowed branch
  - Gridscan to adjust branch #, BR and  $E_0$  based on a reference spectrum

**Preliminary**

Branch	BR [%]	$E_0 [Q_\beta]$
#1	2	0.22
#2	22	0.44
#3	56	0.96
#4	20	1



### Quality of nuclear data

- Acceptable: ENSDF, TAGS, Direct  $\beta$
- Questionable: potential Pandemonium
- Poor: isotope with no data



**Still under investigation**

### 3. Revised summation method

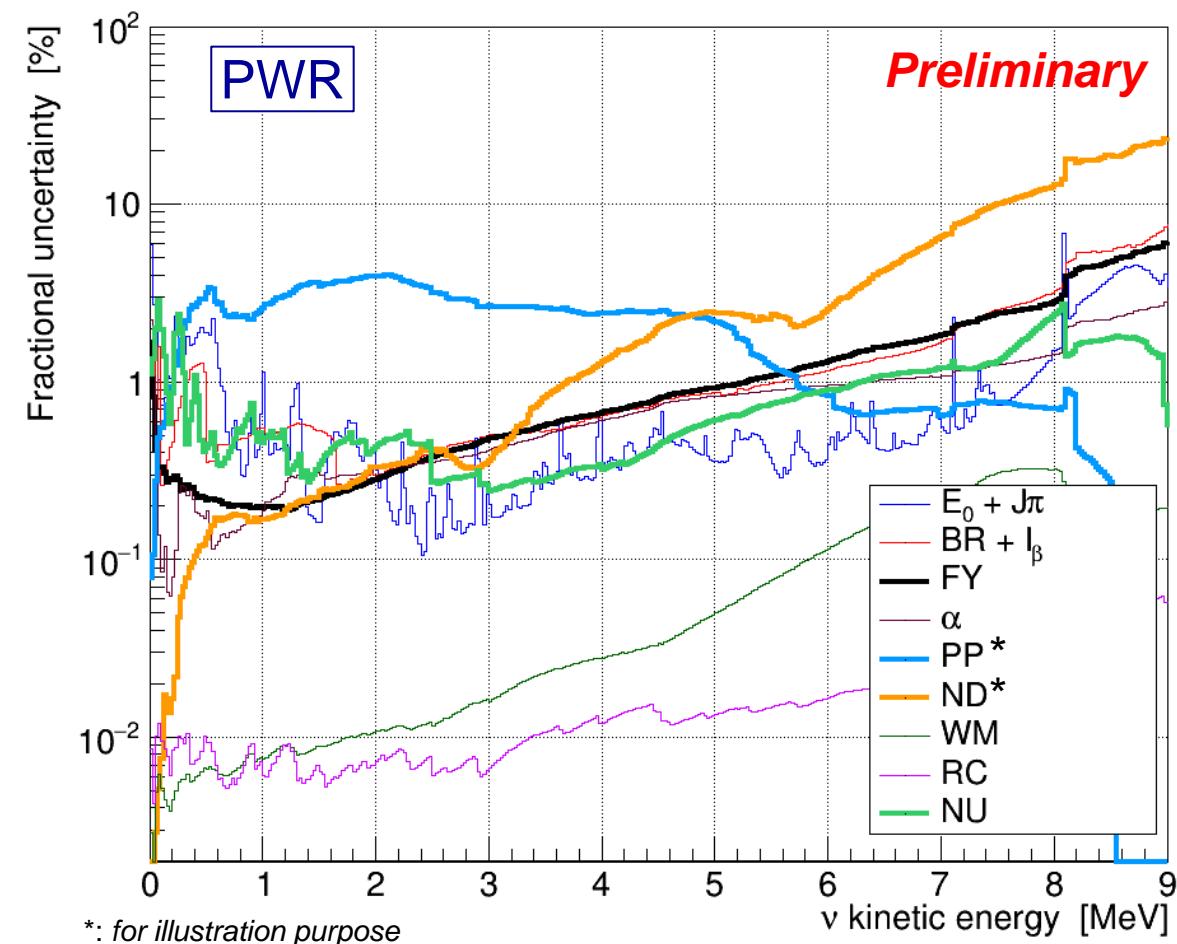
### c. Uncertainty budget

#### NORMALIZATION UNCERTAINTY

PWR		
$\langle \sigma_{IBD} \rangle$		$6.46 \times 10^{-43} \text{ cm}^2/\text{fission}$
<b>Uncertainty [%]</b>		
$E_0 + J\pi$	MC	0.2
$BR + I_\beta$	MC+Analytic	0.5
<b>Potential Pandemonium (PP)</b>	Model comparison	<b>~2</b>
<b>Isotopes with no data (ND)</b>	Model comparison	<b>&gt;2</b>
<b>FY</b>	Analytic	<b>0.7 - 5</b>
$\alpha$	Analytic	0.7
<b>Weak magnetism (WM)</b>	Model comparison	<0.1
<b>Radiative correction (RC)</b>	Model comparison	<0.01
<b>Non-unique transitions (NU)</b>	Model comparison	<b>&gt;0.3</b>
• main		0.2
• others ( $\xi$ -approx)		>0.2
<b>IBD cross-section</b>	Analytic	0.1
<b>Total</b>		<b>&gt;3</b>

: Preliminary budget, work in progress

#### FRACTIONAL UNCERTAINTY



⇒ Uncertainty budget dominated by FY, PP and ND

⇒ Uncertainty budget expected to be  $\geq 3\%$

# OUTLINE

## 1. Introduction & motivations

- a. Reactors as antineutrino sources
- b. Experimental anomalies

## 2. Different modeling methods

- a. Conversion method
- b. Reactor data-driven method
- c. Summation method

## 3. Revised summation method

- a.  $\beta^-$  spectrum calculation
- b. Nuclear data content
- c. Uncertainty budget

## 4. Preliminary comparisons

- a. Integral measurements
- b. Spectrum shape

## 5. Conclusion & perspectives

## 5. Preliminary comparisons

### a. Integral measurements

All plots are preliminary

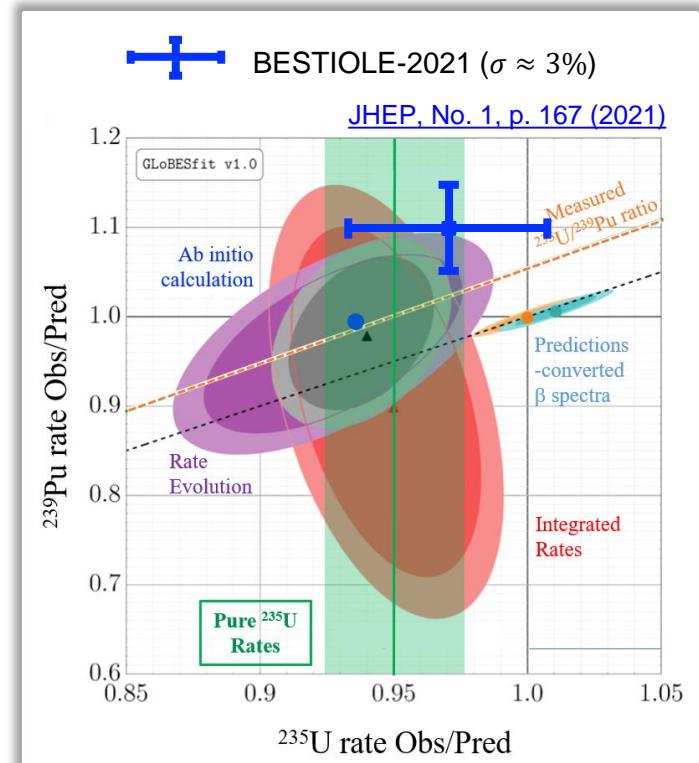
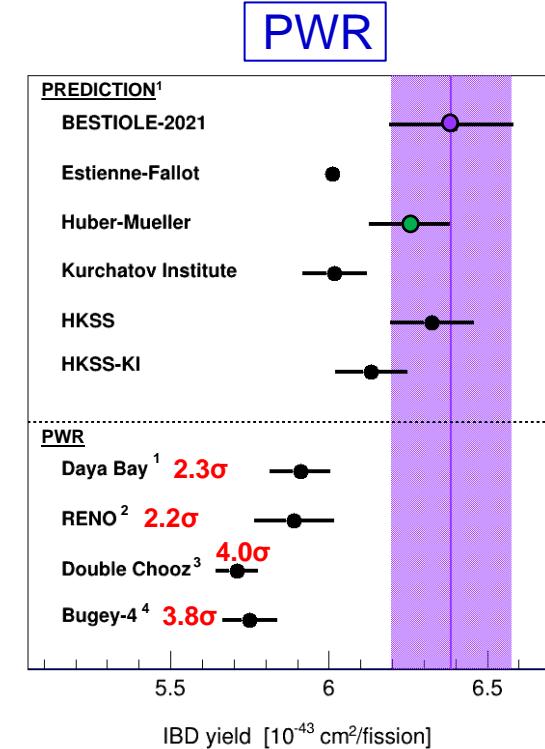
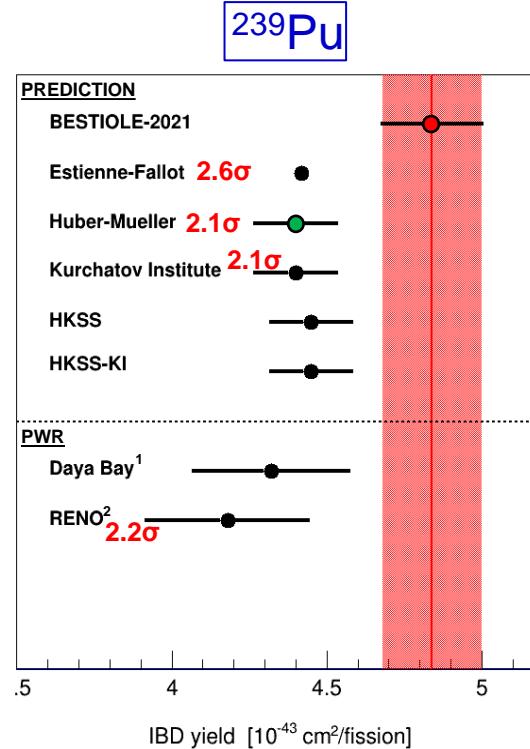
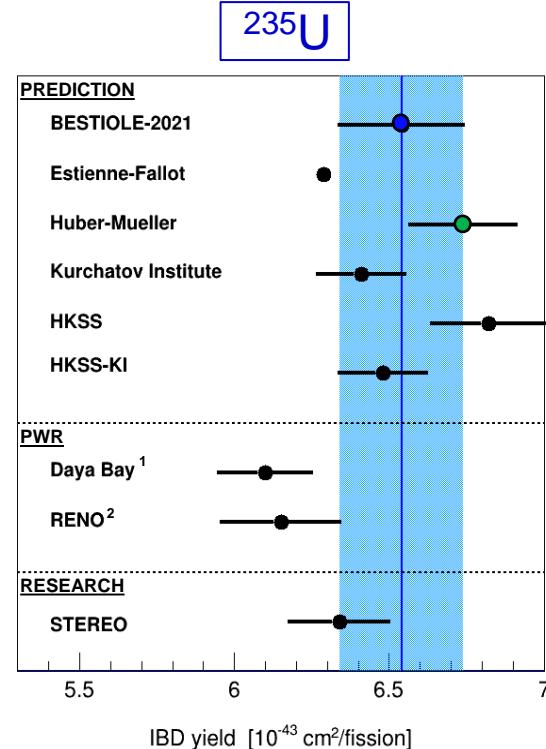
Predictions and <sup>(4)</sup> taken from [Giunti et al., arXiv:2110.06820v1](#)

<sup>1</sup>: Phys. Rev. Lett. 123, 111801 (2019)

<sup>2</sup>: Nature Phys. 16, 558–564 (2020)

<sup>3</sup>: Phys. Rev. Lett. 125, 201801 (2020)

Note: different fission fractions can impact the IBD yields by ~0.5%



- $^{235}\text{U}$  and  $^{238}\text{U}$ : BESTIOLE-2021 consistent within  $2\sigma$  with other data
- $^{239}\text{Pu}$  and  $^{241}\text{Pu}$ : not consistent with other data ( $\geq 2\sigma$  for  $^{239}\text{Pu}$  and  $\geq 3\sigma$  for  $^{241}\text{Pu}$ )
  - ▷ Important contribution of isotopes with no data in BESTIOLE-2021
  - ▷ Associated uncertainty must be larger than 2%

$$\text{DB/ B-21} = 0.925 \pm 0.014 \text{ (exp)} \pm 0.028 \text{ (model)}$$

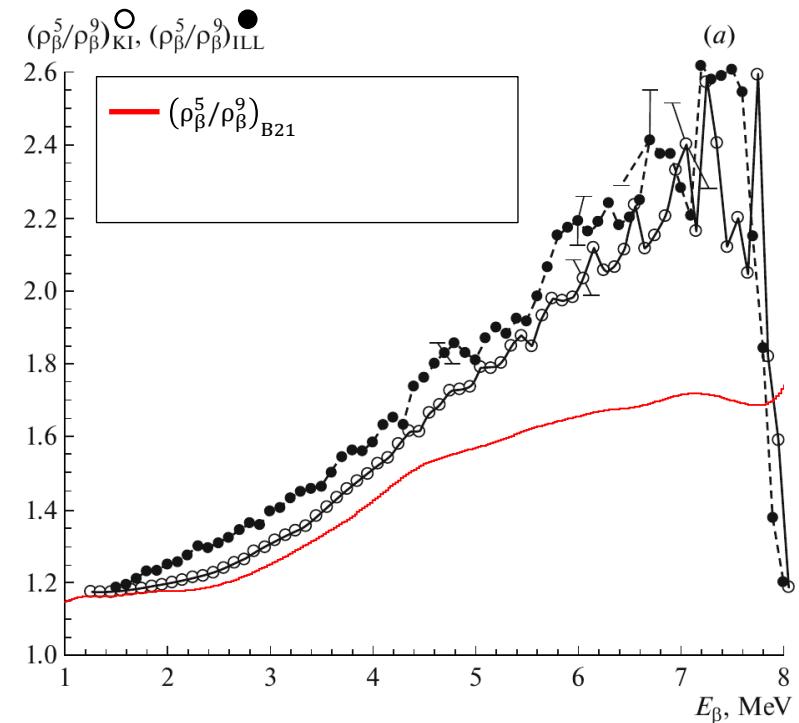
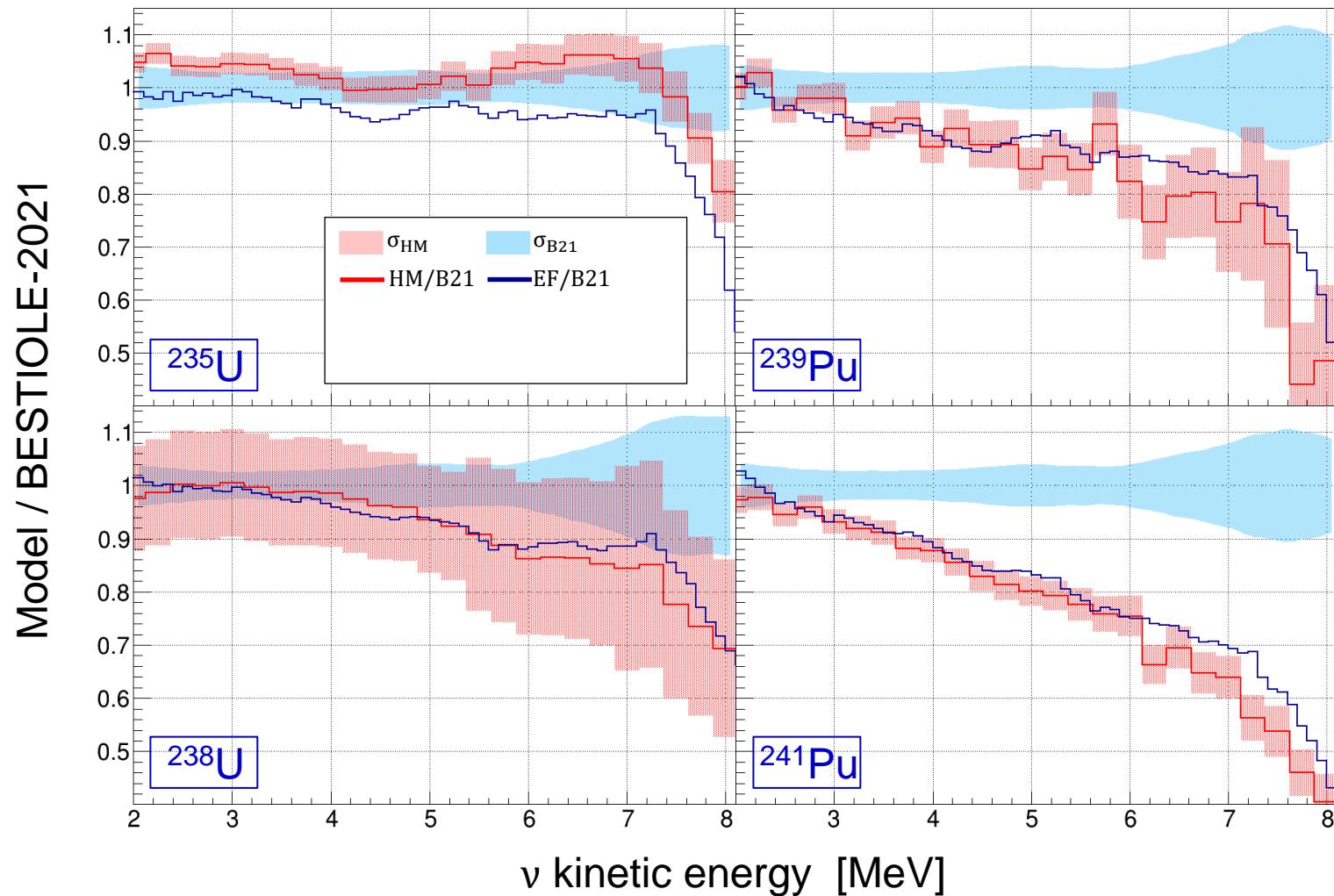
$$\text{DB/ HM} = 0.945 \pm 0.014 \text{ (exp)} \pm 0.018 \text{ (model)}$$

⇒  $2.3\sigma$  significance in both cases

## 5. Preliminary comparisons

### b. Spectrum shape

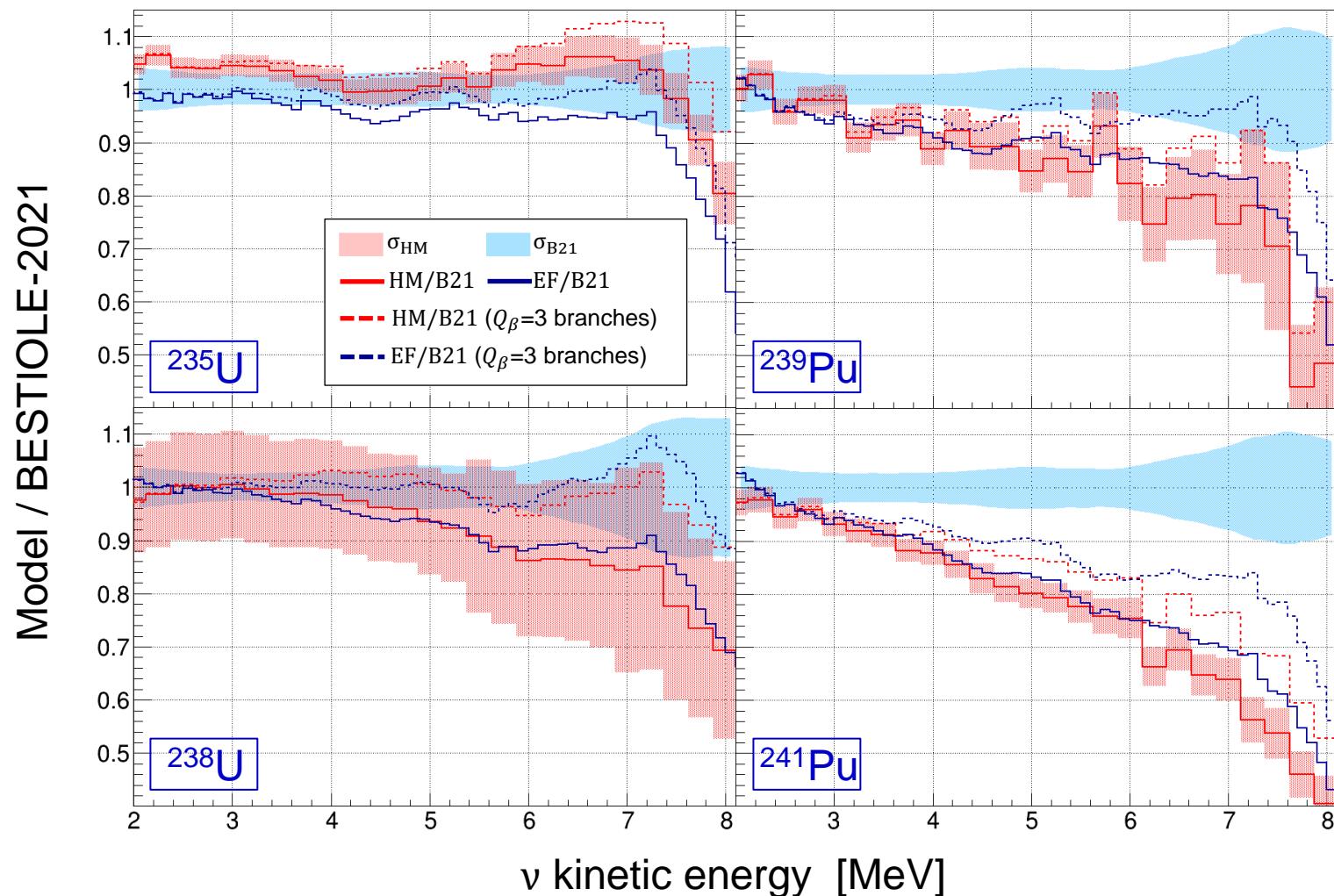
All plots are preliminary



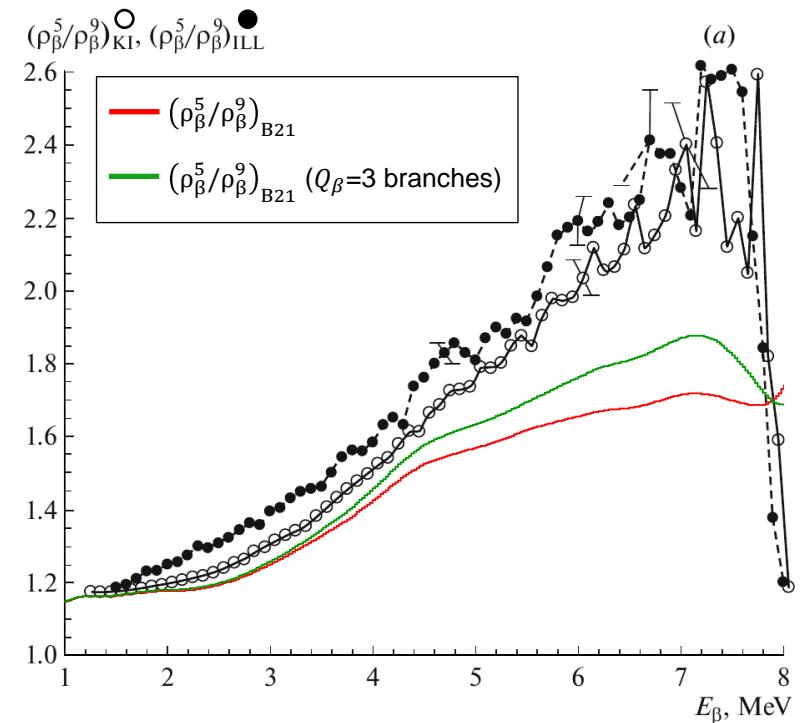
## 5. Preliminary comparisons

### b. Spectrum shape

All plots are preliminary



### IMPACT OF EFFECTIVE MODEL



⇒ Important impact of the modeling of isotopes with no data

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### KEY POINTS OF A SUMMATION PREDICTION

#### Modeling of non-unique forbidden transitions

- IBD yield **decreased by 1.5%**

#### Include recent TAGS data

- IBD yield could be **decreased by ~2%** → uncertainty

#### Modeling isotopes with no data

- The choice of the model can impact the spectrum shape and IBD yield by **several %**

#### Comprehensive uncertainty budget

- **On-going effort** to evaluate potential mismodeling ( $\xi$ -approximation, uncorrected Pandemonium, isotopes with no data)

⇒ **Expected final uncertainty budget  $\geq 3\%$**

## BESTIOLE-2021 (current state)

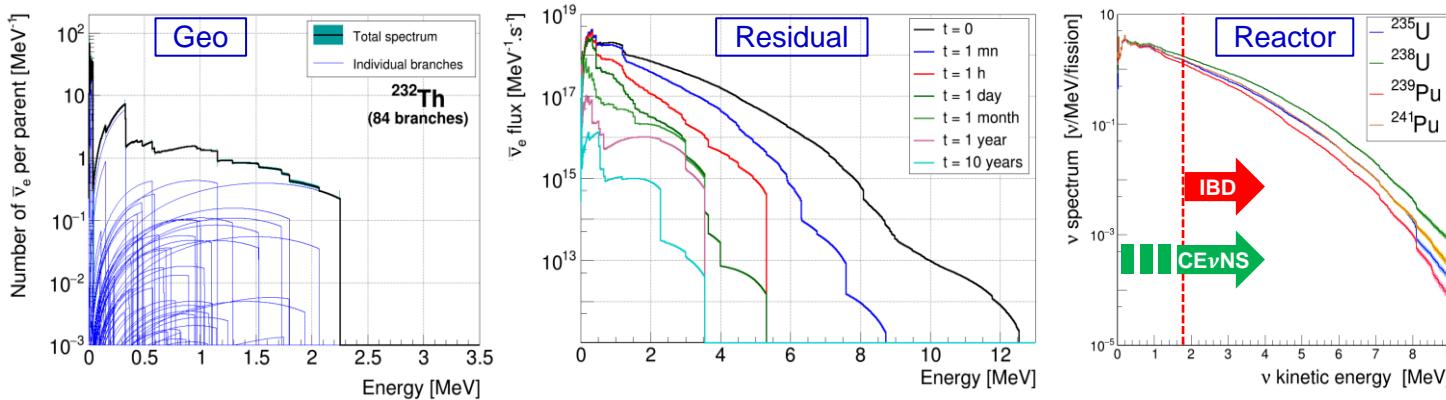
### IBD yields ( $10^{-43} \text{ cm}^2/\text{fission}$ )

$^{235}\text{U}$ :	$6.54 \pm 0.20^*$
$^{238}\text{U}$ :	$10.81 \pm 0.40^*$
$^{239}\text{Pu}$ :	$4.84 \pm 0.16^*$
$^{241}\text{Pu}$ :	$7.23 \pm 0.26^*$

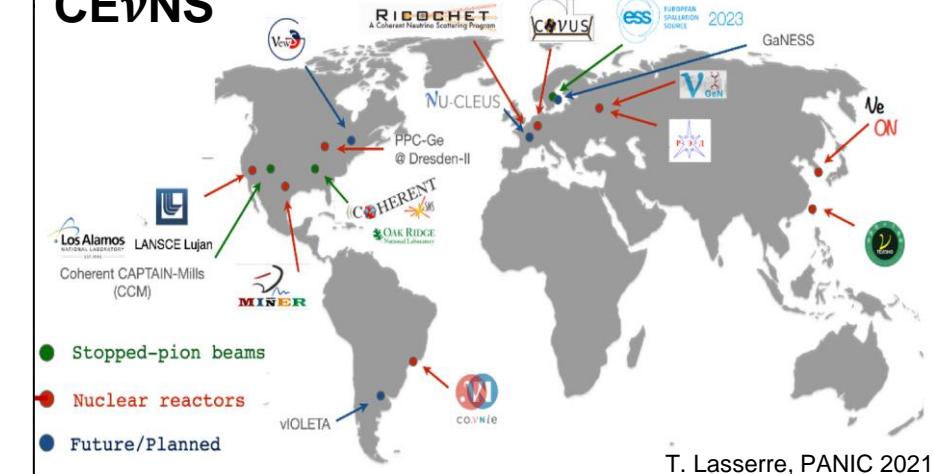
⇒ Detailed comparison with other models & measurements once the uncertainty budget is completed

\*Preliminary uncertainty budget, expected to increase

### Reach of a finalized summation model



### CE $\nu$ NS



T. Lasserre, PANIC 2021